Extended Abstract
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SRTM On-Orbit Structural Dynamics

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1. Introduction

The Space Radar Topography Mission (SRTM) flew in February 2000 on the space shuttle Endeavor as the primary payload for STS-99. The objective of this joint project between the National Imagery and Mapping Agency (NIMA) and the National Aeronautics and Space Administration (NASA) is to generate a near-global high-resolution database of the earth's topography. This mission made use of Interferometric Synthetic Aperture Radar (ISAR) to digitally survey the earth's surface from space. The primary product of this 11-day mission a topographic database of 80% of the earth's land surface, i. e. most land surfaces between ± 60° latitude. The resulting digital terrain data set provides a significant improvement over currently existing global topography data sets.

1.1 Instrument Overview

The SRTM architecture is based upon the Spaceborne Imaging Radar/X-band Synthetic Aperture Radar (SIR-C/X-SAR) instruments which flew twice on the Space Shuttle Endeavor in 1994, see Jordan et al, 1995. The SIR-C/X-SAR project was a collaborative effort between NASA, which developed SIR-C, and the German and Italian space agencies, which developed X-SAR. The SIR-C instrument was two separate SAR's which operate in the C, and L-bands. The X-SAR instrument operates in the X-band. The combined SIR-C/X-SAR instruments including electronics essentially fill the shuttle payload bay. The primary objective of the SIR-C/X-SAR missions was the radar imaging of a select " supersite" targets. SIR-C/X-SAR's secondary objectives, which enabled SRTM, included the demonstration of repeat pass interferometry and scan-SAR. The repeat pass interferometry data is then used to recover the topographical features of the target surveyed. While scan-SAR is a method of beam steering which is employed by SRTM, in the C-band, such that the radar swath width is sufficient to achieve complete mapping coverage in 159 orbits. See Rosen et al for a detailed treatment of Synthethic Aperture Radar Interometry.

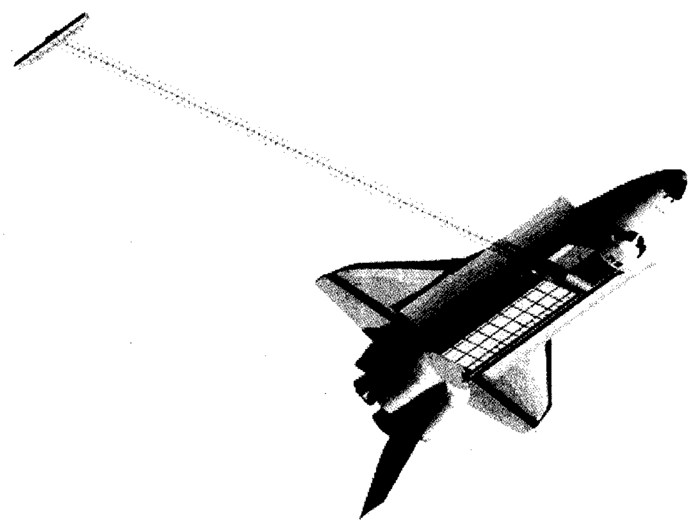

Figure 1. SRTM Mission Configuration

The required modifications to the existing radar instrument to collect the interferometric data included a second C-band antenna, a 60-meter mast, metrology, and additional avionics. Further, the German Space Agency provided a second X-band antenna. The fundamental SRTM instrument configuration is illustrated in figure 1. Simplistically, SRTM makes use two radar apertures separated by a fixed distance, or baseline, to form a fixed baseline interferometer. The in-board aperture, relative to the Orbiter payload bay, is used to both send and receive radar energy while the outboard antenna only receives energy.

One of SRTM's significant features is the use of a 60-meter long deployable mast that serves to deploy an outboard antenna and creates a stable baseline. The structural dynamic issues associated with a 60-meter mast and large tip mass, i. e. the outboard antenna, deployed from the Shuttle are the focus of this paper. Specific topics covered include on-orbit math model development, loads analysis, ground and on-orbit structural dynamic testing. Additionally, a novel approach towards the reduction of mast on-orbit transient response called "Fly-casting" is developed from first principles, and in-flight performance of this technique is described.

1.2 Antenna Mechanical System (AMS)

The original SIR-C/X-SAR instrument is illustrated in figure 2. The top surface of SIR-C/X-SAR, i. e. the C-band panels and L-band panels, is 12 meters by 3.5 meters and is tilted approximately 14 degrees relative to the orbiter xy plane. SIR-C/X-SAR's three primary structural mechanical components: a) the Antenna Core Structure (ACS), b) the X-SAR Support Structure (XSS), and c) the Antenna Trunnion Structures (ATS).

The ACS is a conventional bolted/riveted aluminum truss which provides support to the L-band and C-band radar panel arrays. The ACS also provides cabling and waveguide support, and incorporates X-SAR assembly hinge and actuator mounting provisions. The original SIR-C/X-SAR instrument flew one row of 18 C-band panels and 2 rows of 9 L-band panels. SRTM retained the 18 C-band panels, and 6 of the L-band panels. SRTM did not use the L-band panels. The panels are attached pseudo-kinematically to the ACS via four standoffs.

The XSS provides the mounting surface for X-SAR's X-band radar panel arrays. The entire X-SAR assembly, i. e. XSS and panels, is connected only to the ACS and is articulated about the STS x-axis via a tri-drive actuator. X-SAR is launched in a stowed position which is within the STS payload bay dynamic envelope, and then is rotated about a hinge line to its on-orbit position which exceeds the dynamic envelope.

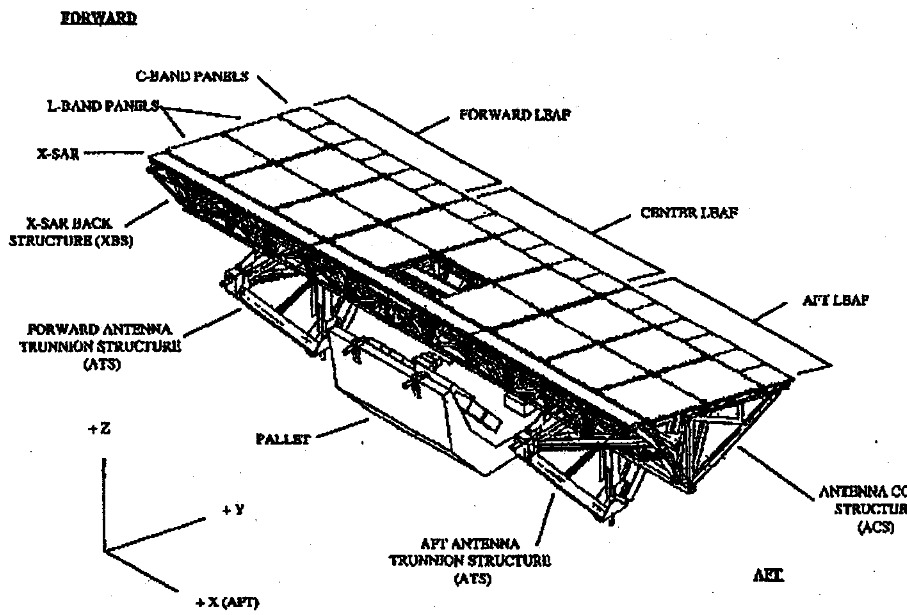

Figure 2. SIR-C/X-SAR

The ATS is the structure that attaches the ACS to the orbiter. Each of the two ATS's (one forward, and one aft) attaches the orbiter in six degrees of freedom, through two sill trunnions, and one keel trunnion. The ACS is then supported on the two ATS's, via a set of linkages, in near statically determinate manner.

The additional SRTM hardware added to the SIR-C/X-SAR instrument is illustrated in figure 3. The most significant addition is the Outboard Antenna System (OASYS) and its deployment system. Also shown in figure 3 is the additional metrology and avionics equipment mounted to the AODA Sensor Panel (ASP). Not shown specifically in figure 3 is the AODA Electronics Plate (AEP) mounted on the ACS aft end, and a pair of propellant tanks mounted in the ACS interior which are part of an SRTM specific cold gas thruster system. The OASYS is comprised by the a) Outboard Support Structure (OSS), b) outboard C-band panel array, c) outboard X-band panels and electronics, and d) AODA equipment. The OSS is a graphite epoxy and aluminum honeycomb bonded structure which then supports the remaining OASYS equipment. The total weight of the OASYS is 877 lbs.

The OASYS deployment system includes the a) 60-meter mast, b) a mast damping system, c) OASYS fliphinge, and d) an OASYS pitch and yaw attitude adjustment mechanism. The 60-meter deployable truss and its deployment mechanisms are described by Gross and Messner. A photograph of the deployed mast is shown in figure 4. The mast damping mechanisms were designed to achieve high, i. e. greater than 10%, damping ratios in the deployed mast first bending modes and the first torsional mode. The OASYS fliphinge rotates the OASYS 180 degrees from its stowed postion to its deployed position once the mast has been deployed. The OASYS pitch and yaw attitude is adjusted via "warpable" truss called the "Milkstool."

1.3 Attitude and Orbit Determination Avionics (AODA)

The SRTM configuration includes an instrumentation package known as the Attitude and Orbit Determination Avionics (AODA) system, see Duren 1998. AODA provides two fundamental measurements, 1) interferometer baseline measurement and tracking, and 2) SRTM instrument position and attitude reference to inertial space. The interferometer baseline measurement is accomplished via to separate measurements. The baseline length is, i. e. distance along the mast, is measured by laser range finders which shoot from the AODA Sensor Panel (ASP) to a corner cube array mounted on the OASYS. The OASYS transverse displacement and attitude is measured by tracking the motion of 3 LED's, mounted to the OASYS, with the ASTRO's Target Tracker (ATT). The ATT is essentially a star tracker that has been refocused to 60 meters. The ATT and LED's are also used during the mast structural identification pulse tests, which are described in a following section.

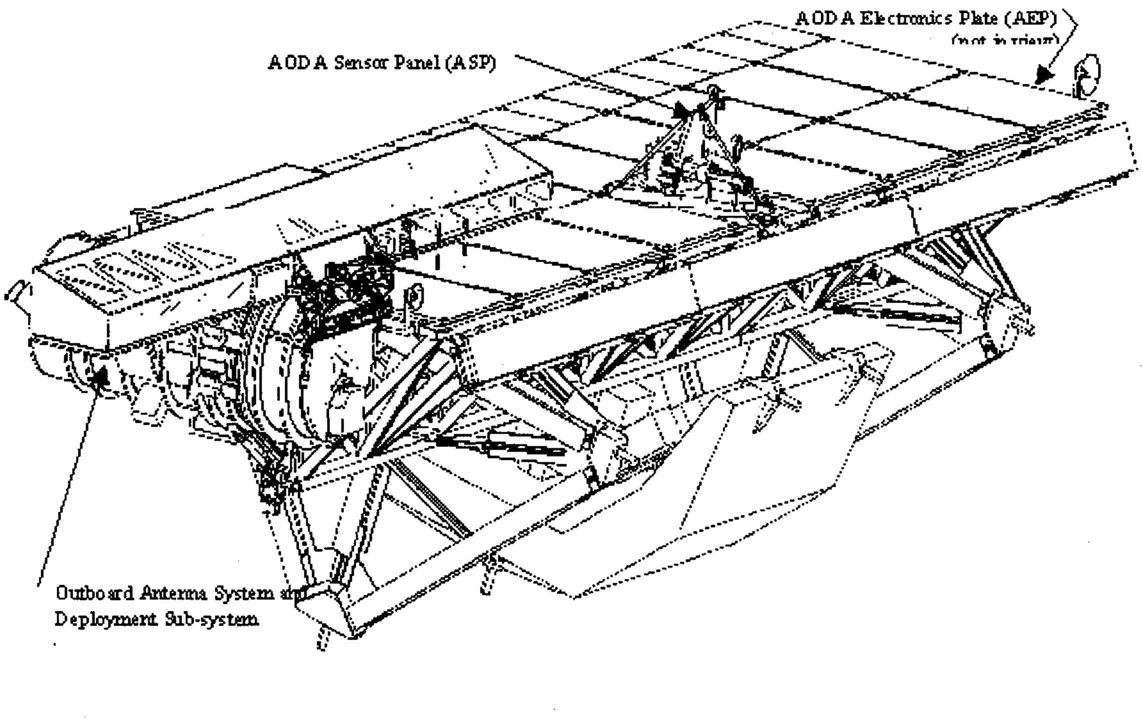

Figure 3. SRTM Stowed Configuration

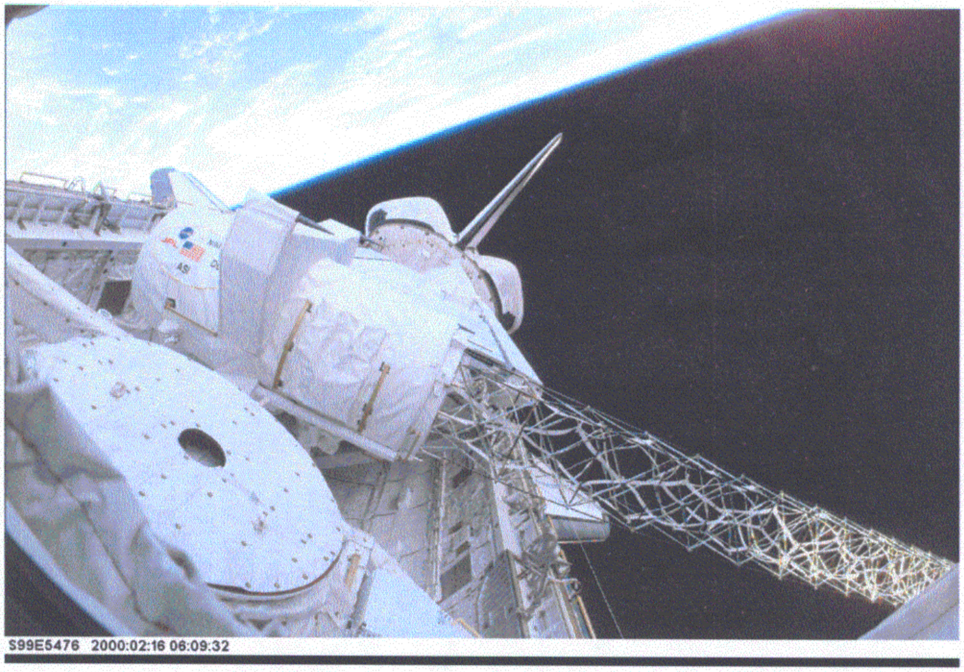

Figure 4. SRTM deployed mast

2. Analysis and Design

2.1 Structural Dynamic Model

JPL created an SRTM on-orbit structural dynamic math model, which was then provided to the various organizations within the STS program who perform various structural dynamic analyses. Specifically, Charles Stark Draper Laboratories (CSDL) provided the flight control design and assessment, on-orbit loads support, and procedure development. Boeing North America (BNA) also provided on-orbit loads support. In total, there were three independent organizations performing on-orbit analysis functions, which provided a good check against integrated modeling and analysis errors. Table one provides a summary of the analytical on-orbit SRTM structural dynamic characteristics as well as a comparison of the results as provided by JPL, CSDL, and BNA.

The SRTM mast damping system utilized fluid filled damping cartridges, which were then modeled as viscous dampers in the analytical assessments. Further, the dampers were tuned such that high damping was achieved in the system's low frequency vibration modes.

2.2 Fly-Casting

An orbit trim burn was performed approximately once a day to make up for orbital altitude loss due to aerodynamic drag effects on the deployed mast. Orbital altitude maintenance was required to ensure proper C-band swath width and overlap. The orbit trim burns were performed using two of the Orbiter's +X Primary Reaction Control System (PRCS) jets located in the tail. Each of these jets applies 880 lbs thrust to the Orbiter, and combined applies an approximately 7.5 milli-g acceleration to the system. This inertial acceleration combined with the discrete tip mass, and the mast distributed mass creates a bending moment at the mast root which can then result in significant mast longeron loads. Further since the thrust from the PRCS jets is applied almost instantaneously, mast transient response effects must also be considered. SRTM employed a novel technique, called "Fly-casting," in order to minimize the mast transient response during the daily trim burn.

The fly-cast trim burn was initiated by a timed +X-jet on-time and off-time followed by an on-time of sufficient duration required to achieve the desired delta-V. A generic fly-cast profile is given in figure 5. The effect of the initial jet pulse and wait sequence is to cause the mast to deflect from its unloaded equilibrium position to a new equilibrium deflection that is associated with the rigid body inertial acceleration. In effect the initial pulse and wait causes the mast to deflect and the main pulse catches the mast in a deflected state just at the instant when the mast has zero kinetic energy in the dominant vibration mode. Based on analysis of a single degree of freedom system it is seen that the system transient response is minimized when the initial pulse and wait period duration's are each one-sixth of the system's natural period. For SRTM the primary mode excited by the +X jets during the orbit trim burn is mode number seven of table 1, the first yaw bending mode. The pre-flight estimate of this frequency was 0.096 Hz, implying that the fly-cast timing is 1.74 sec. This timing parameter is further rounded to the nearest even multiple of 80 msec, which is the Orbiter Digital AutoPilot (DAP) update rate.

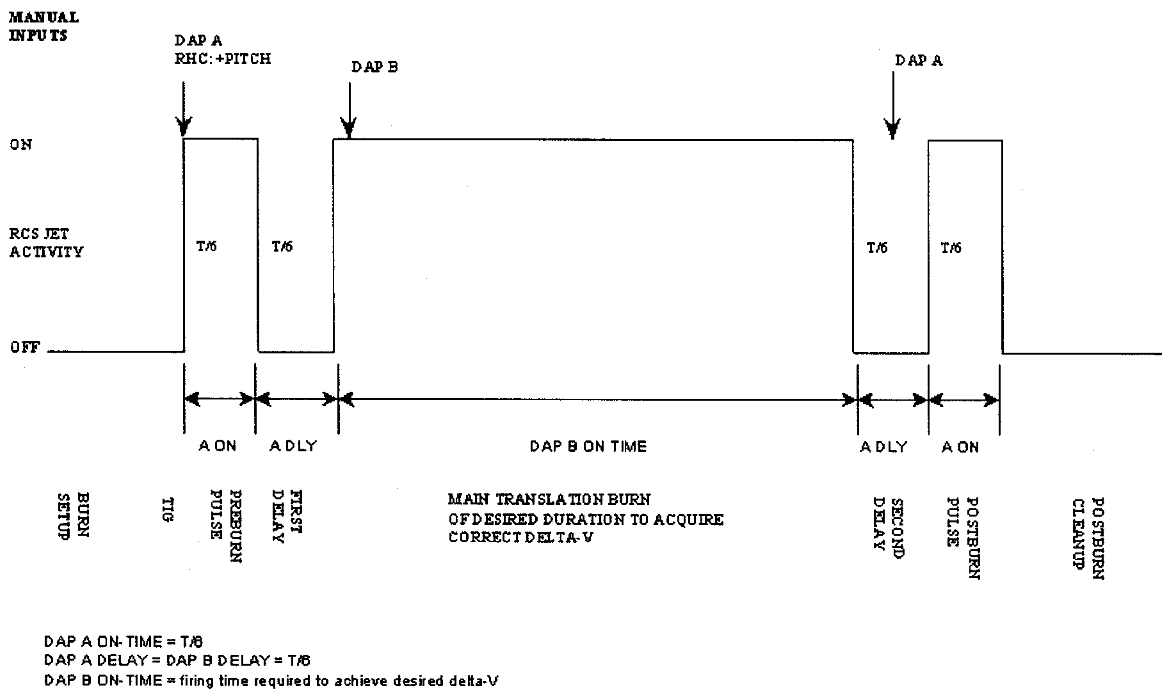

Figure 5. Typical Fly-cast Burn Timing

4. Fly-Casting in Practice

A total of seven fly-cast trim burns were attempted and completed during the SRTM mission. The fly-cast timing parameter of mast yaw mode period over six was determined experimentally to be 1.76 sec (rounded to the nearest 80 msec). The total delta-V applied ranged from 2.9 to 5.1 fps. The main burn duration ranged from 8.8 to 18 sec. A time history of the mast tip deflection for the first fly-cast burn is illustrated in figure 6. An ideal fly-cast configuration was realized for SRTM in part due to the failure of the mast damping system to generate any damping force which left the system lightly damped.

6. Acknowledgments

The effort described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

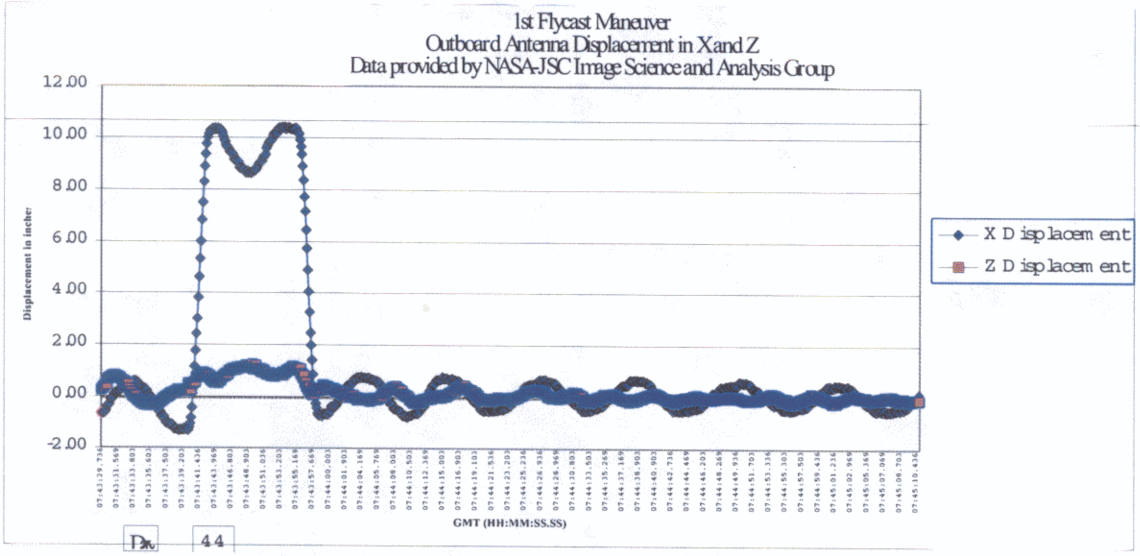

Figure 6. Typical Fly-Cast Burn Time History

7. References

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